PATHFINDER

AUTONOMOUS RENDEZVOUS & DOCKING PROGRAM PLAN

December 1988

PATHFINDER

Office of Aeronautics and
Space Technology

National Aeronautics and
Space Administration
Washington, D.C. 20546

FOREWORD

Project Pathfinder is a research and technology program which will allow the National Aeronautics and Space Administration (NASA) to strengthen the technology base in support of the civil space program and enable a broad set of new space missions. Through Pathfinder, the NASA Office of Aeronautics and Space Technology (OAST) will develop a variety of high leverage technologies that will support a range of future missions including a return to the moon to build an outpost, piloted missions to Mars, and continuing exploration of other planets.

NASA's potential missions to the moon and to Mars will require the use of orbiting spacecraft with smaller modules that will go to and from the lunar or planetary surface. The capability for autonomous rendezvous and docking with the orbiting element is required for both manned and unmanned missions. The Pathfinder Autonomous Rendezvous and Docking Project will develop and validate the technologies for this new capability. The project will focus on the development of sensors and mechanisms, trajectory control requirements and techniques for operations in lunar and planetary orbits, and associated guidance, navigation, and control algorithms. Prototype hardware and software will be developed and demonstrated in test beds, flat-floor facilities, and in flight.

For additional information on the Autonomous Rendezvous and Docking Project or this document, please call the OAST Information Sciences and Human Factors Division (RC), at ext. 2743.

GLOSSARY

AI	Artificial Intelligence
AR&D	Autonomous Rendezvous and Docking
B-V-L	Battin-Vaughan-Lambert (rendezvous algorithm)
DDT&E	Design, development, test, and evaluation
DOF	Degrees of Freedom
DRM	Design Reference Mission
EMC	Electromagnetic Compatibility
FY	Fiscal Year
GN&C	Guidance Navigation and Control
GPS	Global Positioning System
JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
LaRC	Langley Research Center
MMU	Manned Maneuvering Unit
MSFC	Marshall Space Flight Center
MRSR	Mars Rover/Sample Return (Mission)
MYE	Man-year equivalent
NASA	National Aeronautics and Space Administration
NSTS	National Space Transportation System
OAST	Office of Aeronautics and Space Technology
OEXP	Office of Exploration
OSF	Office of Space Flight
OSS	Office of Space Station
OSSA	Office of Space Science and Applications
PASO	Program and Specific Objectives
P/F	Pathfinder
RTOP	Research and Technology Objectives and Plans
RF	Radio Frequency
SDIO	Strategic Defense Initiative Office
SE&I	Systems Engineering & Integration
WBS	Work Breakdown Structure

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SECTION 1

INTRODUCTION

1.1 Objectives of this Document

This is the Autonomous Rendezvous and Docking Program Plan. It provides top-level, authoritative guidance and information on the scope, content, and long-range plans of the Autonomous Rendezvous and Docking Program. The objectives of this document are complementary to the Pathfinder Program Plan. This document defines a work breakdown structure, and technical goals and objectives for the Pathfinder Autonomous Rendezvous and Docking element. A management approach, participating center roles and responsibilities, schedules, milestones, deliverables, and long-range plans are defined.

1.2 Pathfinder Program Overview

Pathfinder is an initiative to develop critical capabilities for the future of the civil space program. Pathfinder does not, in itself, represent a commitment to any particular mission. However, through Pathfinder, the NASA Office of Aeronautics and Space Technology (OAST) will develop a variety of high-leverage technologies that can be applied in a wide range of potential future NASA missions. Project Pathfinder is organized into four programmatic thrusts:

(1) Exploration
(2) Operations
(3) Humans-in-Space
(4) Transfer Vehicles.

The Autonomous Rendezvous and Docking Program (AR&D) is one of five elements under Operations. More information on Pathfinder can be found in the Pathfinder Program Plan.

1.3 Mission Studies and Technology Requirements

Pathfinder focuses on capabilities required for both manned and unmanned missions to the Moon and Mars. Most of the mission scenarios require the use of orbiting spacecraft with smaller modules that will go to and from the lunar or planetary surface. Rendezvous and docking operations are required. Autonomous rendezvous and docking are enabling technologies for unmanned missions where signal delays preclude teleoperations. Autonomous rendezvous and docking are enhancing technologies for manned missions, in which these capabilities reduce crew workload and potentially improve performance when long-duration missions affect the currency of piloting skills. Precursor missions such as the Mars Rover/Sample

Return (MRSR) are an application of autonomous rendezvous and docking.

The AR&D Program involves dual development paths, keyed to the readiness levels of enabling technologies and mission requirements. Near-term demonstrations of AR&D capabilities will use technologies which can reasonably attain a Technology Readiness Level of 5 (as defined by OAST; see figure 1) in the FY '90 - '91 timeframe. Far-term demonstrations of AR&D capabilities will incorporate technologies expected to attain a Technology Readiness Level of 5 in the FY '93-'94 timeframe.

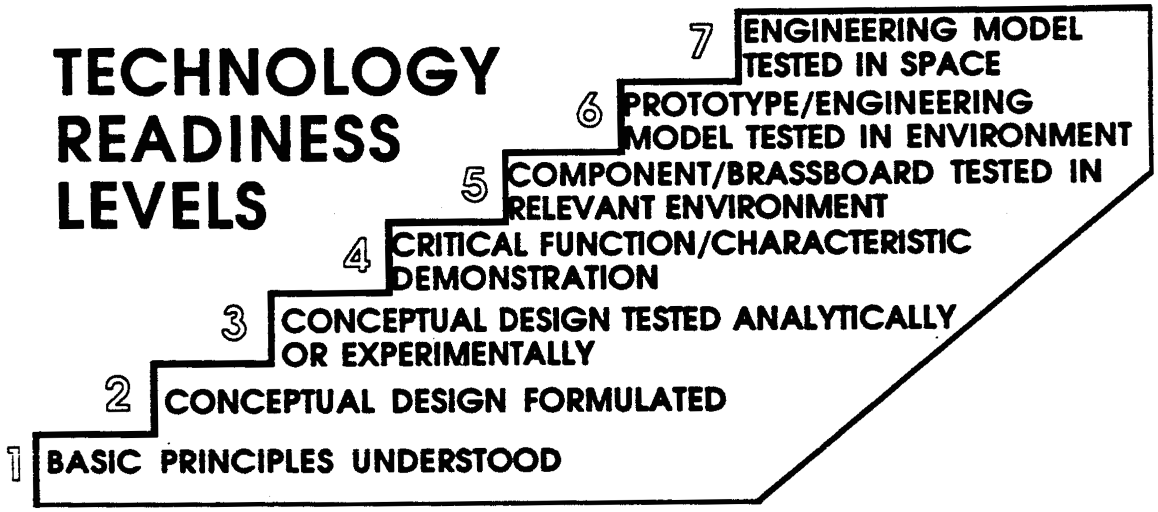


Figure 1 - OAST Technology Readiness Level definition.

1.4 Technology Assessment

There is no currently validated autonomous rendezvous and docking capability. Current methods require extensive ground support and flight crew participation. The rendezvous phases of missions are based on significant ground tracking of spacecraft. The docking phase requires control by an observer on one of the spacecraft. This degree of observation is not available for unmanned Mars vehicles and the communication time delays preclude control through teleoperations from Earth.

Manual rendezvous and docking operations on manned Mars missions require high levels of piloting skills, which would be difficult to retain during the long transit times between Earth and Mars orbits. Automated support to rendezvous and docking of manned Mars vehicles would increase the reliability and performance of these operations. Autonomous navigation and tracking capabilities would still be required because of the limitations of ground tracking in a Mars orbit and the communication time delays between the Earth and Mars orbit.

Implementation of autonomous rendezvous and docking requires development of several critical technologies: (1) sensors for long- and short-range navigation; (2) guidance, navigation, and control (GN&C) algorithms and trajectory control techniques for rendezvous and docking of manned and unmanned vehicles in lunar or planetary orbits; and (3) docking mechanisms which are unique to the Mars environment and accommodate long-periods of dormancy.

Measurements of relative position, velocity, attitude, and attitude rates are critical to rendezvous and docking operations. The onboard rendezvous sensors on the Shuttle (star tracker, rendezvous radar) are inaccurate with respect to performance expectations for planned unmanned systems, and require extensive crew monitoring. By design, they are inadequate for ranges less than 90 feet. Shuttle rendezvous systems were designed with manned operations and typical Shuttle missions in mind, hence their unsuitability to Pathfinder goals and objectives. Radars being considered for the Orbital Maneuvering Vehicle will also be ineffective at very close ranges. The Global Positioning System (GPS) can provide relative navigation in low Earth orbit, but its performance and space application must be proven. GPS will not be adequate for close-range maneuvering and docking. No suitable long-range radars are available which meet the power, weight, and performance goals of the Mars Rover/Sample Return Mission.

The AR&D Program will develop sensors for short and long-range navigation, with the goal of meeting the total set of navigation requirements with a minimum suite of sensors. Emphasis will be placed on maximum applicability of these sensor technologies across the span of Pathfinder missions. The AR&D Program will make maximum use of current technology developments. As an example, a prototype laser docking sensor that is being developed for a flight experiment on a Shuttle flight, could support terminal rendezvous, station keeping, approach, and docking. This sensor can provide navigation measurements from zero to three miles. Further work is needed to enhance the applicability of this sensor to the Pathfinder Program. Its effective operating range must be extended, while reducing its power, weight, and volume. Other candidate sensors such as millimeter radar and vision systems require further evaluation and development.

For Pathfinder, it is anticipated that a near-term AR&D demonstration can be accomplished by modifying or expanding the capabilities of existing or emerging sensor technologies. However, an advanced sensor such as a vision sensor will require longer development time to attain sufficient maturity for a demonstration. Such advanced sensors will be targeted for a far-term AR&D demonstration.

Autonomous guidance, navigation, and control (GN&C) algorithms do not currently exist, either for rendezvous or docking, but are not thought to be major technology drivers. However, significant work is required to focus their designs on mission constraints unique to the Pathfinder missions. Current GN&C designs focus on constraints associated with manned vehicles and include lighting conditions and continuous space-to-ground communications. Onboard manual control provides the final docking operations. The Pathfinder missions may not be subject to these constraints, but require an emphasis on reliability of the rendezvous and docking operations. Cooperative control and automatic maneuver selection, execution, and recovery are major design challenges. An alternative navigation system may be required for rendezvous operations conducted at ranges of thousands of nautical miles.

The docking mechanisms which have been or are being developed for manned vehicles are expected to be adequate for manned Pathfinder missions. However, unique mechanisms will have to be developed for small, unmanned vehicles such as the Mars Ascent and Orbiter Vehicles. The AR&D Program will focus on the specific technology drivers associated with Pathfinder mission applications. These include extended service life in hostile environments with long periods of dormancy, high system reliability, high levels of autonomy for unmanned vehicle operations, and severe restrictions on power and weight. While the AR&D Program will support these technology developments, the actual development of mechanisms will be a project responsibility.

1.5 Autonomous Rendezvous and Docking Program Goals and Objectives

The long-term goal of the Autonomous Rendezvous and Docking Program is to develop, validate, and demonstrate autonomous rendezvous and docking capabilities to support manned and unmanned vehicle operations in lunar and planetary orbits. In the early phase of this program, the system requirements will be defined for candidate Pathfinder mission applications and correlated with specific technology requirements. A near-term demonstration of AR&D capabilities will be developed incorporating existing or emerging technologies to verify proof of concept. The demonstration will consist of ground demonstrations.

A far-term demonstration will be developed to provide proof of concept for advanced sensors, which require long-lead time development. The corresponding GN&C algorithms and trajectory control techniques will be developed and the integrated system will be tested in ground demonstration.

1.6 Technical Approach

For candidate Pathfinder mission scenarios and corresponding vehicle configurations, coordinated systems-level rendezvous and docking requirements will be defined. Performance requirements for AR&D hardware and software will be established.

Hardware and software technologies to meet these requirements will be identified and current technologies will be assessed for applicability. AR&D capabilities will be segregated into near- and far-term programs, based upon readiness levels of required technologies and specific Pathfinder mission plans.

Maximum synergism between near and far-term programs will be implemented, with major differences expected in the technologies of the relative navigation sensors. Trajectory control requirements and techniques for AR&D will be defined and candidate GN&C designs will be developed to implement these AR&D capabilities. Six and twelve degree-of-freedom simulations will be used for performance, dispersion and sensitivity analyses and trade studies of the integrated designs.

Results of these evaluations will be used to establish the specifications for prototype sensors. Prototype sensors and hardware/software emulations will be developed and incorporated into test bed proof-of-concept demonstrations. Results of synergistic technology and advanced development programs, such as the laser docking sensor flight experiment, will be incorporated into the program. Flat-floor facilities will be used for ground demonstrations of the final docking operations.

Figure 2 depicts the progression from requirements definition, to development of system level performance requirements, preliminary development, and finally to ground based tests that comprise Pathfinder AR&D development. The figure shows the interdependency of the various tasks as well as the role of program planning in coordinating the execution of these tasks.

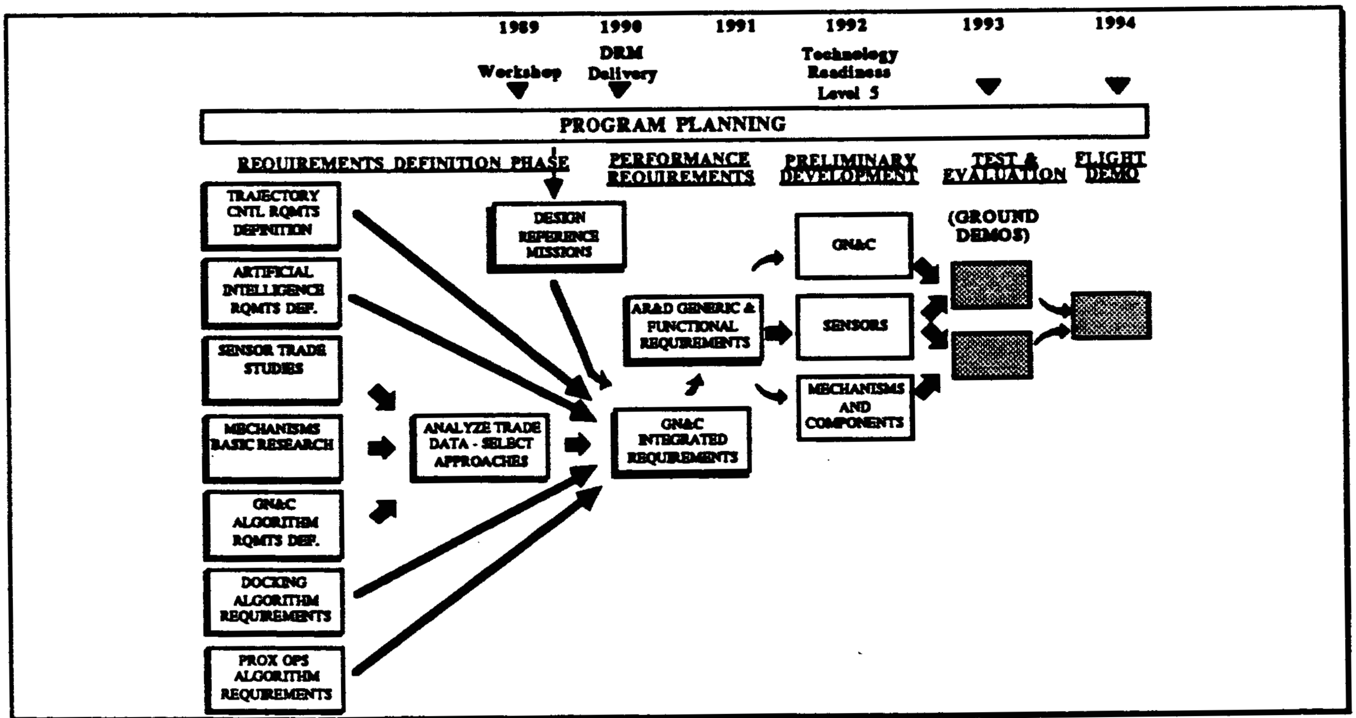


Figure 2 - Technical approach to Pathfinder AR&D DDT&E.

SECTION 2

PROGRAM DESCRIPTION

2.1 Work Breakdown Structure

The Autonomous Rendezvous and Docking Program is divided into three major work packages: (1) Systems Integration; (2) Guidance and Control; and (3) Sensors and Mechanisms. These work packages are structured to provide focus on specific technology development areas.

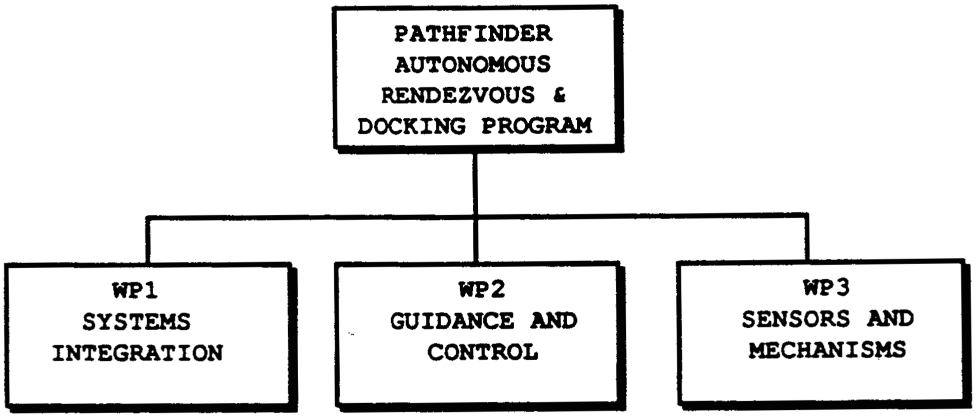


Figure 3 - Pathfinder AR&D Work Breakdown Structure (WBS).

2.2 Management Plan

2.2.1 Management Structure

Figure 4 shows the Lead Center management structure for the Pathfinder AR&D program. Advantages of this type of management structure include clear identification of accountability for project definition, implementation and deliverables, single point of interface between NASA headquarters and the Lead Center and flexibility to dynamically adjust task assignments and resource allocations in a timely manner.

The overall Pathfinder AR&D program will be managed by the Program Manager in Code RC. An intercenter working group including JSC, MSFC, JPL, AMES, LaRC will make recommendations to Code RC regarding AR&D definition and planning and will function as a steering committee to review any appeals to assignments of tasks or resources to the NASA centers.

JSC, as the Lead Center, will provide technical coordination, reporting, scheduling and progress against milestones and will recommend resource allocations and task assignments to Code RC. Participating centers will provide deliverables established in the AR&D Project Plan.

This management structure provides clear definition of accountability while maintaining a formally defined process for negotiation of detailed task assignments and resources to the NASA centers.

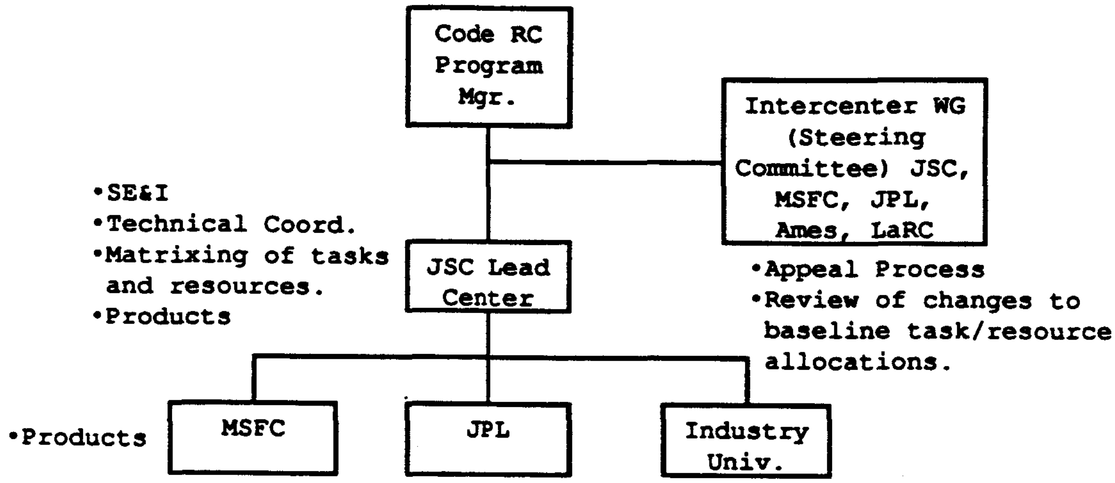


Figure 4 - Management Structure for Pathfinder AR&D Program.

2.2.2 Program Coordination

The AR&D element of Pathfinder is one of several arenas in NASA addressing automation and autonomy of orbital rendezvous and docking. Other arenas include: Code E Mars Rover Sample Return, Code Z Manned Lunar and Mars missions, Code M Satellite Servicing, Assured Crew Return Capability, Logistics Resupply and Servicing, Advanced Development Initiative, Logistics Resupply for Space Station, and Unmanned Shuttle Derivative Vehicles.

The thrust of Pathfinder AR&D is to develop enabling technologies for planetary exploration, which support fully autonomous operations, hostile environments, long periods of dormancy and extremely reliable systems, to a technology readiness level of five (refer to figure 1 for a definition of the various levels).

Cooperative programs will be identified to demonstrate, in low earth orbit, components of Pathfinder AR&D technology which fulfil the objectives of less severe requirements for the other AR&D arenas. This process will require coordination between OAST, OSSA, OSF, OSS and OEXP.

2.2.3 Program Planning

The AR&D Program Plan is an initial five year plan, developed cooperatively with the Lead Center and the participating Centers. This document establishes program content, task assignments, resource allocation and milestones. Formal reviews of tasks by all NASA centers with Code RC will provide a mechanism to modify the program plan as required and to project the focus of long range tasks.

2.3 Resources

2.3.1 Five Year Funding

Resources for the first five years of the program are summarized in figure 5.

WORK PACKAGES	FY 89 ($K)	FY 90 ($K)	FY 91 ($K)	FY 92 ($K)	FY 93 ($K)
SYSTEMS INTEGRATION	305	700	850	900	700
GUIDANCE AND CONTROL	400	1150	1750	2000	1800
SENSORS AND MECHANISMS	185	1150	2400	3100	3500
Estimated NASA Work Force (MYE)	**4.5**	**5.5**	**8**	**8**	**8**
TOTALS	**890**	**3000**	**5000**	**6000**	**6000**

Figure 5 - Pathfinder AR&D Five Year Funding and Work Force.

2.4 Systems Integration

2.4.1 Objectives

The objectives of this work package are to provide program planning and control support, systems engineering and integration of the hardware and software technology developments, and continuing coordination of the program element's activities with Pathfinder Program directions. Autonomous Rendezvous and Docking involves the development of a number of technologies, with various options within each technology area. A focused systems integration effort is required to establish appropriate priorities, budgets, and systems-level assessments and direction to provide timely and cost-effective fulfillment of the program objectives.

In addition, this work package will provide the systems-level coordination with related technology, advanced development, and flight programs to maximize technology transfer and synergism. Such coordination will include cooperation in National Space Transportation System (NSTS) flight demonstrations of AR&D capabilities, the Code M Advanced Development Initiative for AR&D and satellite servicing, and the Logistics Resupply and Servicing Demonstration.

2.4.2 Technical Approach

The objectives of this work package are achieved by the performance of several tasks including: (1) Program Planning Support, (2) Systems and Mission Analyses, (3) Trajectory Control Analyses, and (4) Guidance, Navigation and Control (GN&C) System Integration.

Systems-level studies are performed to provide direction and focus to the detailed technology development studies. These systems-level studies include the definition of AR&D systems requirements, coordinated with Pathfinder Program mission requirements. The corresponding technology requirements will be defined and correlated to specific Pathfinder mission scenarios. The various options to meet the technology requirements will be assessed to select the most applicable and achievable candidates.

AR&D technology components will be integrated in high-fidelity guidance, navigation, and control (GN&C) simulations to ensure that the individual technologies meld into a viable and effective system design. These simulations will also be used to compare various technology options.

As the AR&D technologies mature to prototype development, this work package will establish the requirements for proof of concept demonstrations. For ground demonstrations, the test plans and facility usage plans will be developed and coordinated. For flight demonstrations, sponsoring organizations will be sought and support for the manifesting process provided.

2.4.3 Schedule

Figure 6 presents the schedule for the activities under this work package. The schedule reflects the implementation of near- and far-term AR&D demonstrations. It supports consolidation of mission requirements into corresponding AR&D system and trajectory requirements in FY '89 and FY '90.

Workshops/technical interchanges will be conducted at the end of the third quarter of each fiscal year. The focus of the FY '89 workshop will be the status of development of GN&C algorithm options and trade studies of candidate sensors.

Parallel technology options will be evaluated and selected during FY '90, incorporating effects of DRMs and updates to mission requirements. Technology thrusts will be segregated into near and far-term capabilities. For the near-term capabilities, trade studies may dictate continued parallel developments into FY '91 for promising technologies. Refinements to high-fidelity simulations will be completed to support these evaluations and integrated GN&C requirements validation and performance evaluations.

The focus in FY '91 will be AR&D system performance analyses to assure that the emerging technologies will support the selected near-term missions. Ground demonstrations will be planned and implemented. Results of the flight demonstration of a laser docking sensor (independent of the Pathfinder Program) will be incorporated into the AR&D Program.

In FY '92, the ground demonstrations of near-term AR&D capabilities will transition to flat-floor demonstrations for the final phases of docking operations. Prototype AR&D hardware and software will be integrated into these demonstrations. Planning for flight demonstrations may be initiated.

The schedule for the far-term demonstration parallels that for the near-term demonstration. Much of the systems and mission analyses and trajectory control analyses will be performed in FY '89 and FY '90 to maximize synergism with the near-term capabilities. Refinements to these studies will be performed in FY '93, keyed to the technology readiness of the advanced sensors.

WORK PACKAGE MILESTONES/DELIVERABLES	FY 89	FY 90	FY 91	FY 92	FY 93
AR&D PRELIMINARY RQMTS REVIEW (PRR) - SYSTEM REQUIREMENTS CORRELATED TO MISSION REQUIREMENTS AND DRMs - TRAJECTORY CONTROL REQUIREMENTS - INTEGRATED GN&C REQUIREMENTS		▲ Near-Term			▲ Far-Term
AR&D SYSTEM DESIGN REVIEW - FINAL SYSTEM REQUIREMENTS - FINAL TRAJECTORY CONTROL RQMTS - FINAL INTEGRATED GN&C RQMTS		▲ Near-Term			▲ Far-Term
AR&D PRELIMINARY DESIGN REVIEW - GN&C OPTIONS EVALUATIONS - VALIDATED SYSTEM RQMTS - PERFORMANCE ENVELOPE DEFINITION			▲ Near-Term		▲ Far-Term
AR&D GROUND DEMONSTRATIONS - PLANS			▲ Near-Term		▲ Far-Term
- RESULTS ANALYSES					▲ Near-Term

Figure 6 - Pathfinder AR&D Systems Integration milestones and deliverables.

2.5 Guidance, Navigation, & Control

2.5.1 Objectives

The purpose of this work package is to support the identification, development, and assessment of Guidance, Navigation, and Control (GN&C) technologies, algorithms, and techniques applicable to the problem of Autonomous Rendezvous and Docking. GN&C development will be directed at supporting AR&D operations in low earth orbit, lunar and planetary orbits, as well as interplanetary trajectories.

Areas of interest to GN&C include:

Development and refinement of general purpose rendezvous guidance schemes (i.e Battin-Vaughan-Lambert formulation).

Optimization (i.e. time, fuel, etc.) of rendezvous trajectories (6 DOF optimal control).

Cooperative control methodologies involving multiple active vehicles.

Trajectory control requirements, techniques, and boundary conditions and their impact on GN&C system performance requirements.

Mass properties identification and compensation.

Guidance and control aspects of maneuver sequence abort criteria definition and implementation of abort sequences.

Detection and avoidance of hazardous conditions.

GN&C system failure detection, fault tolerance, redundancy requirements, and techniques for automatic system reconfiguration.

Application of Artificial Intelligence (AI) and expert systems technology to GN&C tasks.

GN&C analysis, development, and evaluation will be phased such that early demonstrations of desired capabilities can be supported. These demonstrations will initially be ground based experiments. By their nature, the GN&C algorithms, techniques, and formulations produced under the GN&C work package element can be tested and evaluated using digital simulations. If the opportunity arises, testing in the actual environment with flight type hardware interfaces will be pursued.

2.5.2 Technical Approach

The primary focus of the GN&C development work package task is to identify the requirements for a self contained autonomous rendezvous and docking algorithm. Two classes of docking targets have been identified: cooperative (characterized as having some type of docking aid such as a transponder, beacon, or reflector array), and noncooperative (not equipped with any docking aid). Additionally, rendezvous targets that are both active and passive in terms of maneuvering, attitude control, and powered/unpowered tracking aids will be addressed. The special GN&C requirements posed by uncontrolled or tumbling targets will be assessed. Specific GN&C requirements imposed by each target class will be delineated,with an objective for the GN&C designs to accommodate both the near-term sensors and advanced sensors.

The GN&C requirements on relative bearing, range, range rate, and attitude data will be assessed against the performance of candidate sensors. In this fashion, performance requirements and capabilities will be traded between the GN&C suite, sensors, and effectors and docking mechanisms. An example of the interaction of requirements between GN&C and effectors/mechanisms is in the robustness of the docking system. A sophisticated, highly accurate GN&C system would permit the use of a simple and very limited (with respect to range of operation, impact attenuation capacity, etc.) docking mechanism. Similarly, a highly capable docking mechanism could tolerate uncertainties in the terminal conditions of the docking sequence that a less refined GN&C complement might introduce. This trade of responsibilities and functional capabilities among the various work package elements will result in an integrated mission system as opposed to a loose collection of point designs.

The requirements on trajectory design and trajectory control will be evaluated for the MRSR mission. For AR&D operations, the traditional mission design constraints such as lighting and communications and tracking coverage that characterize manned operations, will be supplanted by requirements for reliability and robustness of the automated sequence in earth, lunar, or Mars orbits.

Artificial intelligence (AI) and expert system technologies will be evaluated for applicability to GN&C systems for AR&D. Use of AI is expected to yield a system that is capable of a variety of responses to external stimuli as opposed to a more limited "canned" set of routines and procedures. It is expected that the MRSR mission operations conducted in Mars orbit will rely to some extent on AI due to the requirement for robust autonomous operations because of the prohibitive light travel time from earth.

2.5.3 Schedule

The schedule for Pathfinder AR&D Guidance, Navigation, and Control development activities is presented in figure 7.

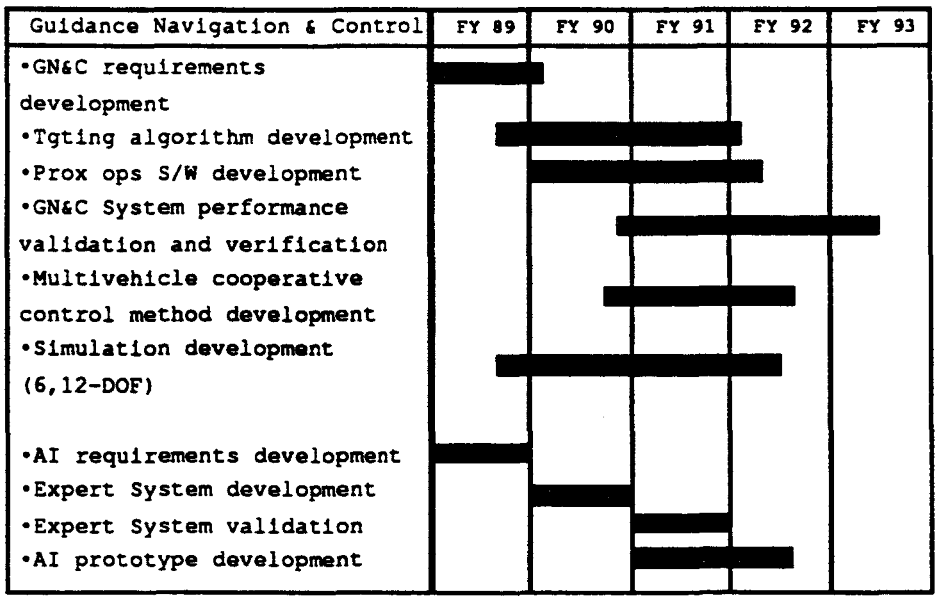


Figure 7 - Pathfinder AR&D GN&C development schedule.

2.6 Sensors and Mechanisms

2.6.1 Objectives

This work package element will provide the Pathfinder Program with sensors, effectors, and mechanisms that satisfy the requirements of AR&D in earth, lunar, and Mars orbits. Generic requirements for all Pathfinder sensors and effectors include low power consumption, weight, and form factor, reliable operations in varying and hostile environments, and operation in these environments after protracted periods of dormancy.

When practical, existing devices and techniques for fabrication and operation of these devices will be adopted for Pathfinder AR&D support. It is possible that certain devices will require novel approaches because it will prove prohibitively expensive to modify an off the shelf product in response to performance requirements. In such cases, the sensors and mechanisms work package will support the development of new devices for Pathfinder.

It is the objective of this element to take a sensor or mechanism from a conceptual stage, through detailed requirements assessment, design, development of prototypes, performance evaluation, and testing. The test and evaluation protocol will range from computer simulations, to ground based test, and culminates with a flight demonstration in the actual environment.

2.6.2 Technical Approach

Sensor and mechanism development begins with definition of the requirements for autonomous rendezvous and docking. These requirements will be derived from the Design Reference Mission (DRM) for the specific program to be supported, initially the Mars Rover Sample Return (MRSR) mission.

Emphasis will be placed on developing sensors that satisfy MRSR long range target detection, acquisition, and tracking and short range accuracy and resolution of range, closure rate, relative attitude, relative body rates, and relative bearing. It is likely that an increase in the performance of existing sensors (particularly with respect to range) will be sought. An early decision will be made as to whether a single sensor can satisfy all mission requirements or if a suite of several sensors offers a more expedient solution. An early goal of this work package is to perform and analyze the results of a trade study to identify those sensor technology development areas that are cost effective, improve performance and will reduce development and schedule risks. These technologies include optical and radio frequency tracking and active versus passive detection.

As candidate sensor approaches proceed from concept, through simulation, breadboard, and finally to prototype phases, the result of each development phase will be subject to test and evaluation either through digital simulation or in a test bed facility. The sensor prototypes will be tested in thermal/vacuum facilities and incorporated in demonstrations using flat-floor facilities. The product of each phase will be made available to other AR&D work packages such that integrated system level tests can be performed.

The effectors and docking mechanisms that will be employed for Pathfinder in general, and MRSR in specific, are not a radical departure from the current state of the art. They will be similar in nature to other devices currently under development for manned space vehicles. The reduction in system size and weight and in total power requirements, coupled with prolonged exposure to hostile environments, are the problems to be attacked in developing the mechanisms for MRSR. To meet these challenges, the following course of action will be adopted:

Identify and define requirements for high reliability, light weight, low power consumption docking mechanism components such as latches and load attenuators.

Investigate basic technologies in the areas of lubrication and seal materials and techniques for long term exposure to hostile environments.

Mechanism requirements for anticipated Lunar and planetary auto-docking systems will be assessed.

Trade studies will be performed to identify preferred approaches to mechanism development from among the following candidates:

Active versus passive latch actuation
Active versus passive load attenuation
Active versus passive target capture
Materials and lubrication options
Thermal protection techniques
Debris exclusion and sealing techniques

As was the case with sensor development, priority is put on selecting a single approach early to minimize dilution of resources among many potential avenues of exploration. An external agent (i.e. from industry or academia) may be selected for execution and analysis of the mechanism selection trade studies.

At the appropriate level of maturity, the selected mechanism design will be subject to test and evaluation on facilities ranging from digital simulations of mechanism behavior to flat-floor dynamic load tests. In all cases, the models and prototypes will be made available to other program elements for integrated tests and total system verification. A balance is essential between the characteristics and capabilities of the mechanisms, sensors, and

GN&C system of the MRSR. An aggressive policy of disseminating requirements and performance data among all Pathfinder work packages will support maintaining this balance.

2.6.3 Schedule

Figure 8 depicts the development schedule for AR&D sensors and mechanisms. Note that for the area of sensor development, a far-term effort succeeds the initial development phase. This far-term activity is likely to concentrate on technologies that permit acquiring and tracking passive or otherwise noncooperative targets at long ranges.

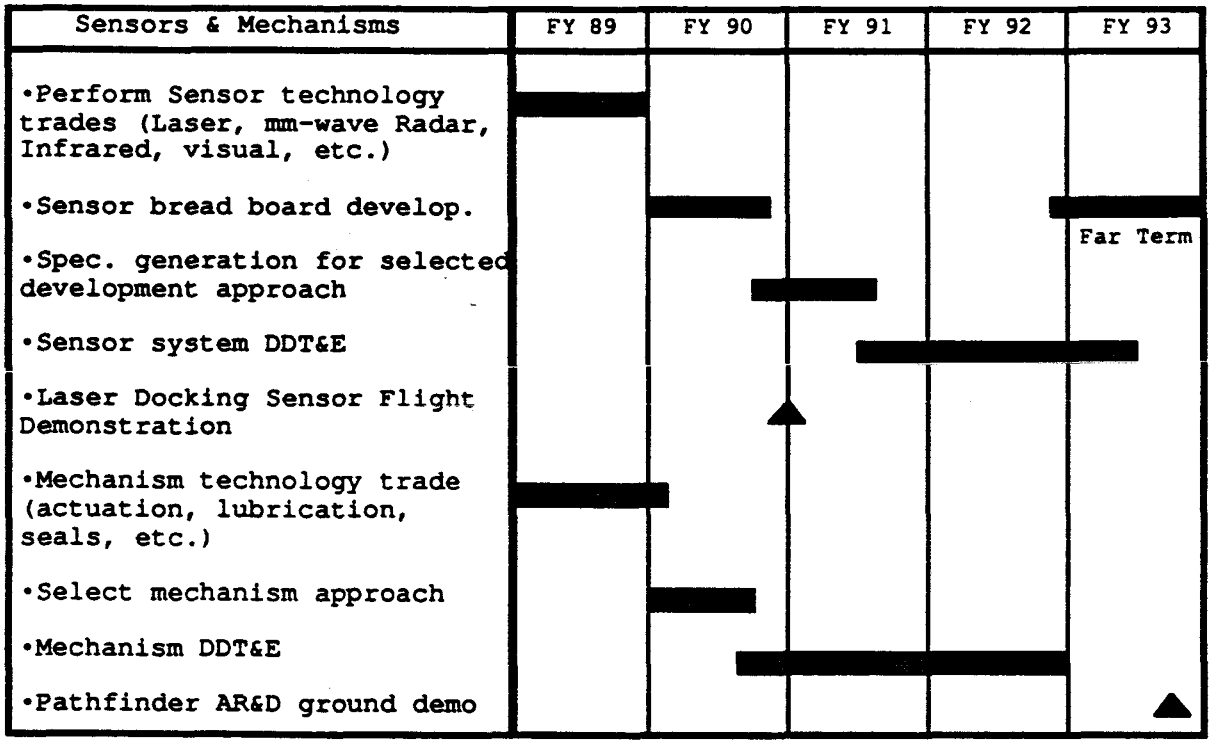


Figure 8 - AR&D Sensor and Mechanisms development schedule.

2.7 Five Year Planning Summary

2.7.1 Fiscal Year 1989 Schedule

The focus of the FY '89 AR&D activities will be to:

- establish AR&D technology requirements, which are correlated to the Pathfinder mission requirements
- define preliminary requirements for trajectory control and GN&C systems

•initiate development of GN&C algorithm options

•assess the requirements and benefits of artificial intelligence to support AR&D

•perform sensor trade studies

•initiate basic research in mechanism technologies, correlated to the unique requirements for Pathfinder missions.

The schedule for FY '89 is provided in figure 9.

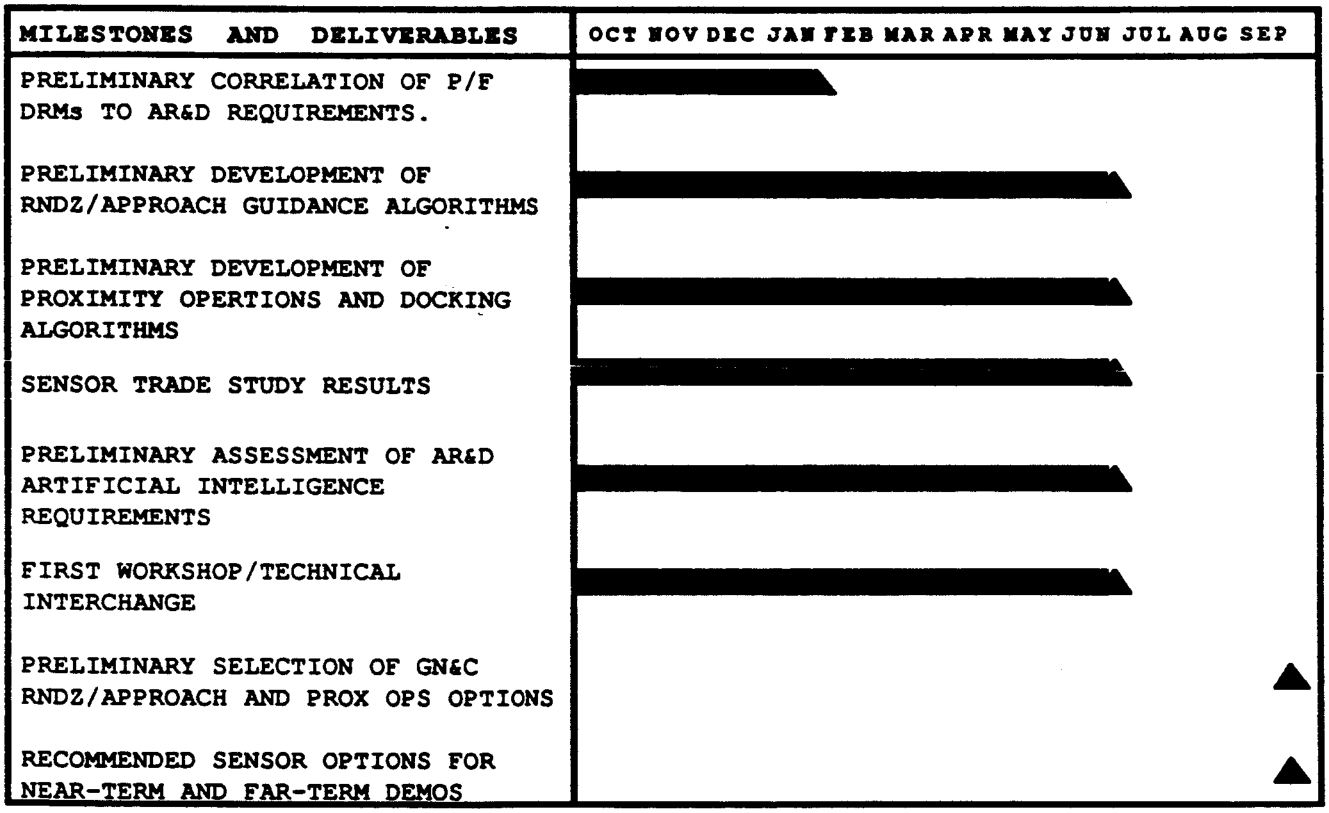
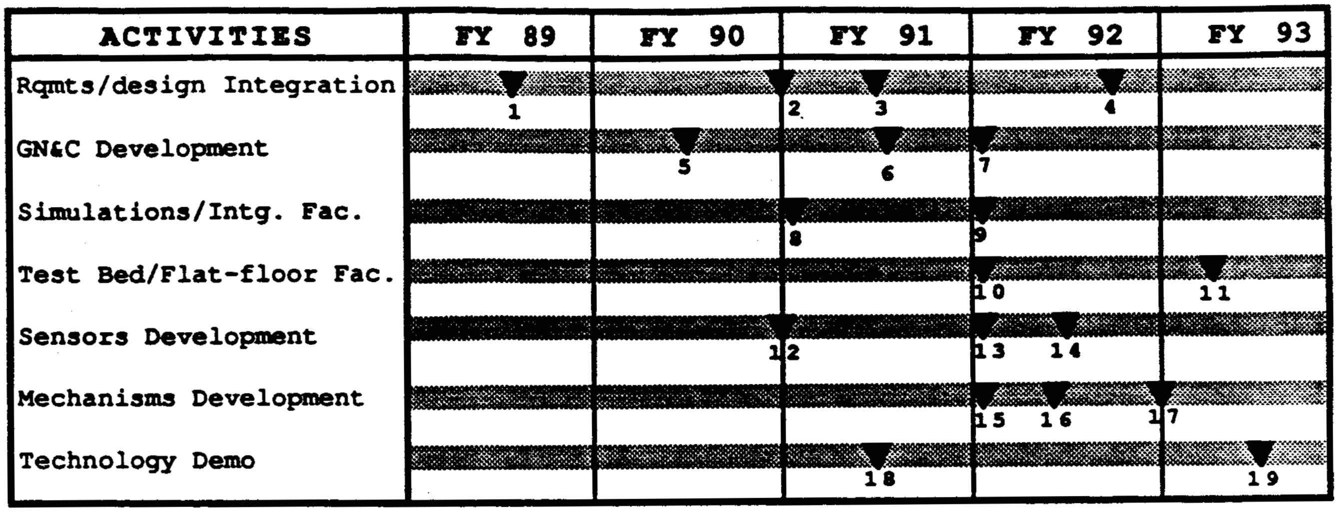


Figure 9 - Fiscal Year 1989 Schedule and Deliverables.

2.7.2 Five Year Schedule

The five-year AR&D schedule is directed toward ground demonstrations of near-term AR&D capabilities in FY '93. In parallel, activities will be performed to support ground demonstrations of far-term AR&D capabilities (with emphasis on advanced sensors) in FY '96. A top-level schedule is defined in figure 10.



DELIVERABLES

1 - TECHNOLOGY REQUIREMENTS DEFINED
2 - NEAR-TERM MISSION REQUIREMENTS/SCENARIO DEFINED
3 - NEAR-TERM GROUND DEMONSTRATION TEST PLAN PUBLISHED
4 - FAR-TERM MISSION REQUIREMENTS/SCENARIO DEFINED
5 - NEAR-TERM GN&C POINT DESIGNS VERIFIED
6 - NEAR-TERM INTEGRATED GN&C PROGRAMS VERIFIED
7 - NEAR-TERM GN&C PROGRAMS INSTALLED IN FLAT-FLOOR FACILITY
8 - 12 DOF SIMULATION OF NEAR-TERM AR&D CAPABILITIES CERTIFIED
9 - NEAR-TERM AR&D CAPABILITIES DEMONSTRATED IN 12 DOF SIMULATION
10 - FLAT-FLOOR FACILITY(S) CERTIFIED FOR NEAR-TERM AR&D DOCKING DEMONSTRATIONS
11 - FLAT-FLOOR DEMONSTRATION OF NEAR-TERM AR&D CAPABILITIES COMPLETED
12 - NEAR-TERM SENSOR(S) BRASSBOARD/BREADBOARD COMPLETED
13 - NEAR-TERM SENSOR TEST ARTICLE INSTALLED IN FLAT-FLOOR FACILITY
14 - THERMAL/VACUUM QUALIFICATION OF NEAR-TERM SENSOR(S)
15 - MECHANISMS ENGINEERING PROTOTYPE DELIVERED TO MATING TEST FACILITY
16 - THERMAL/VACUUM QUALIFICATION OF PROTOTYPE MECHANISM COMPLETED
17 - ACCELERATED LIFE TESTING OF PROTOTYPE MECHANISM COMPLETED
18 - CODE M LASER DOCKING SENSOR FLIGHT DEMONSTRATION RESULTS ASSESSED
19 - NEAR-TERM AR&D GROUND DEMONSTRATION COMPLETED

Figure 10 - Five-Year Schedule, Milestones and Deliverables.

2.8 Long Range Plan

The Pathfinder AR&D project will build upon a substantial base of piloted rendezvous flight experience obtained from previous NASA programs and conceptual and definition studies for Space Station.

After the 1980's AR&D related technology for sensors, GN&C and mechanisms has been demonstrated and incorporated into funded development programs, there will be an opportunity to refine AR&D strategies to more fully incorporate advances in digital processors, artificial intelligence and superconductor magnetic technologies. With the advent of supercomputer flight computers, the viability of high speed real-time computation may allow for the development of a second generation of AR&D

components that may include passive sensors, magnetic latching, and adaptive mission planning.

The Pathfinder AR&D element will position NASA to take advantage of these opportunities by providing an experienced intercenter team with indepth technical skills in all the requisite AR&D disciplines and associated management mechanisms to define, implement, and control the development of advanced AR&D technologies.

2.8.1 Program Goals

The Pathfinder AR&D program schedule is divided into two parts, a near-term effort to produce usable results within five years, and a far-term effort that will produce more robust components by 1998. For example, in the area of sensor technology, the near-term objective is to develop the technology for sensors to conduct automated rendezvous and docking with an active target vehicle that cooperates with the maneuvering vehicle. However, the far-term goal is to dock with a totally passive target vehicle that provides no active assistance to the maneuvering vehicle. Similarly, in the area of mechanisms, the far-term goal is to develop the technology for docking mechanisms that will produce a universal docking mechanism that is more robust than current concepts under study.

A long term goal of the AR&D program is to develop ways for coordinating the efforts of the different "arenas" so as to have synergism between the technology efforts of the program and the needs of the "arenas" for technology to support them. These arenas may include the Mars Rover/Sample Return (MRSR) Mission, Advanced Development Initiative, Orbital Transfer Vehicle, Block II NSTS, Satellite Servicing, Orbital Maneuvering Vehicle, and Space Station. It is reasonable for the different "arenas" to expect that they not be asked to support an entire technology effort when they have a very specialized requirement that would only use a portion of the developed capability. However, it may be possible to identify sufficiently the technology needs of the hardware program elements to tailor the Pathfinder technology development to satisfy their needs and still maintain the continuity of the Pathfinder AR&D program.

Each arena has different uses for the automated rendezvous and docking capability. It may not be possible to combine all the requirements into one package capable of satisfying all users. Therefore, the Pathfinder project will develop a set of core technology that can then be used by any of the arenas to further develop their desired capability. This level of cooperation may be all that is required to satisfy the arenas. However, if a core set of requirements can be developed that are larger in scope, there may be sufficient synergism and economy of scale to make it worthwhile for the arenas to assist in funding the technology development efforts of the Pathfinder AR&D.

Our goal is to identify a core set of requirements that is common to all arenas and will satisfy 80% of their total capability requirements. If an arena wanted to have the capability, they would then be expected to assume responsibility for completion of the technology development effort using their own resources. At the same time each arena will be encouraged to contribute some resources to the Pathfinder AR&D project to bring the project further along to fruition than if Pathfinder AR&D funding were the sole source. This synergism will allow the project to reach technology demonstration level 5 on schedule, permitting the arenas to then pick up at level 5 and continue their own specialized development activities.

2.8.2 Arenas

Mars Rover Sample Return (MRSR) Mission (Code E and Z)

The requirements for this arena are autonomous operation, high reliability, with low weight and volume. Because the spacecraft will be traveling to and operating at Mars for a lengthy period of time before conducting rendezvous and docking, the system must be highly autonomous and reliable.

Mars/Lunar Piloted Missions

Mars and lunar piloted missions require automated rendezvous and docking capability because of concern about the ability of the crew to function adequately after a prolonged period of reduced gravity or weightlessness.

Advanced Development Initiative, Block II NSTS (Shuttle II), and Orbital Transfer Vehicle (OTV) (Code M)

This arena requires simplified crew interfaces that minimize the amount of interaction the crew must have with the vehicle. Moreover, the AR&D system must be capable of interfacing with the Global Positioning Satellite system to determine accurately the range and range rate data necessary for automated rendezvous and docking.

Satellite Servicing and Orbital Maneuvering Vehicle (Code M)

Satellite servicing using Shuttle-based and Space Station-based OMV's will require supervised autonomous rendezvous and docking capability with the crew "watching" the rendezvous and docking process without taking an active part unless warranted.

NSTS Enhancements (Code M)

The requirements for enhancements to the existing NSTS are unknown at this time.

Space Station (Code S)

The requirements are unknown at this time.

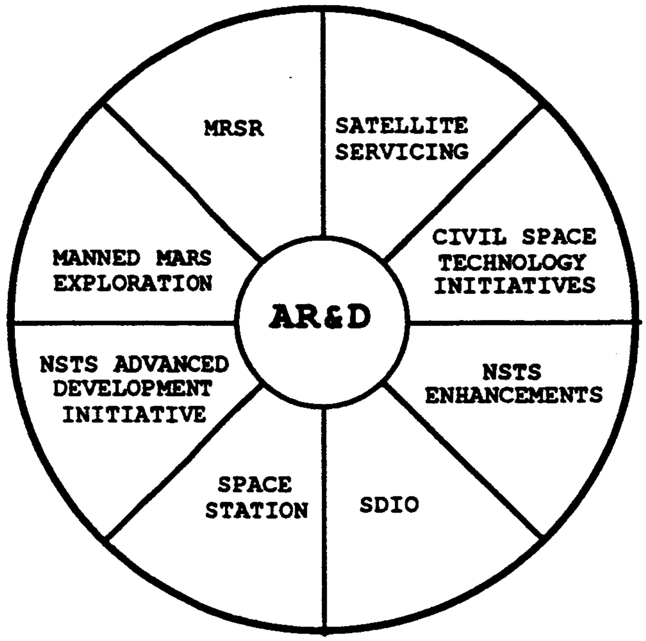


Figure 11 - AR&D development/operational arenas.

SECTION 3

Contracting Plans

3.1 Overview

Implementation of the Pathfinder AR&D Project will include AR&D Systems Engineering and Integration, GN&C and sensor and mechanism products from JSC. MSFC will contribute to the development, testing and demonstration of docking and JPL will contribute to the development of advanced guidance and navigation strategies.

3.2 Industry

Development of AR&D prototype components will be contracted to industry. Early engineering models will be evaluated in NASA laboratory facilities and used to develop concepts for long range AR&D planning.

3.3 Universities

Opportunities to involve universities or non-profit organizations in AR&D technology development will be sought. Possibilities include participation in trade studies of alternative sensor technologies, assessment of AR&D artificial intelligence applications, simulation enhancements and participation in workshops to select competing AR&D approaches.

SECTION 4

FACILITIES PLANS

4.1 Overview

Facilities used in support of Pathfinder Autonomous Rendezvous and Docking (AR&D) fall into two classifications:

1. Laboratories and Computing
2. Demonstration and Testing facilities.

The Pathfinder AR&D project will not require the construction of any new facilities, either for development or for testing. Maximum use will be made of existing and planned facilities, computational resources, etc.

While it is possible that there might be a limited requirement for additional computing capacity, the need will not be on such a scale as to justify investment in a dedicated "brick and mortar" facility. Contractors involved in AR&D support will be expected to supply the requisite floor space and computer hardware resources. This is not expected to present any problem in that the total requirements for AR&D are small, and AR&D code can be hosted in existing government and contractor owned machines. Computer facilities will support the design, development, and test and simulation activities for AR&D. Physical facilities will house test fixtures and related evaluation support equipment.

AR&D test beds and related facilities will be essentially modifications or enhancements to existing facilities. The most significant resource required by AR&D are the flat-floor facilities that will support evaluations and demonstrations. These are existing facilities that will be used on a time sharing basis with other test sponsors.

4.2 Laboratories and Computing

A very mature base of 6 DOF and 12 DOF simulations capable of supporting the Pathfinder AR&D program is available within NASA. These simulations have been used to develop and test the performance of rendezvous and docking for the Apollo, Shuttle, OMV and Space Station programs.

Enhancements to existing software must be defined to support Pathfinder AR&D WBS elements such as automatic proximity operations, artificial intelligence aspects, general purpose guidance algorithms, sensor models, planetary vehicle models, and planetary environment models.

After these enhancements are accomplished and candidate AR&D configurations are established and assessed there will be a need to integrate AR&D components with existing flight vehicles such as NSTS, OMV and expendable vehicles. Very mature simulations of NSTS and OMV are available within NASA and should readily accommodate flight test scenario development and performance assessment.

NASA has made a significant investment in data processing equipment to support general engineering tasks, data base development and interrogation, project management, and information dissemination. An intercenter data communications network is also in place. The Pathfinder AR&D program will make the maximum possible use of this electronic data processing and communications infrastructure.

4.3 Demonstration & Testing Facilities

For the Pathfinder AR&D program, testing begins far earlier than when a physical test unit is available. Testing and evaluation of GN&C and other application software and interface testing starts with simulations and progresses to emulations, or a mixture of emulators, math models, breadboards, and actual flight type hardware. In this sense, the computational resources are demonstration facilities. Computational resources sufficient to meet the needs of Pathfinder AR&D development are distributed across the various NASA centers and among their support contractors.

Flat-floors and air bearing tables of varying sizes and capabilities are located at MSFC and JSC. Pathfinder will not seek to add any new flat-floors, but rather will use existing ones on a time sharing basis, funding additions and enhancements as required.

Throughout NASA and its associated contractors, there exists a variety of space environment simulators. These facilities are variously configured to simulate parameters such as the thermal, radiation, or atmospheric environments in which the AR&D system must perform. Similarly, there are available a number of accelerated testing cells which will support component life cycle testing in terms of exposure to hostile environments, repeated operational cycles, etc. All of these facilities will be employed in the same fashion as the flat-floors. AR&D will approach them as a test sponsor, thus avoiding the requirement for a "brick and mortar" investment.

SECTION 5

In-Space Research and Technology

Technology for rendezvous and docking of piloted space vehicles is very mature and includes historical performance data from actual in-space missions. Translation of piloting techniques to accomplish these critical tasks in an autonomous manner, however, is not straight forward. Flight crews who performed these missions had extensive training preparation in complex man-in-the-loop real-time simulators with realistic visual presentations. Extravehicular-activity provided a rich capability to address anomalies and achieve mission success. Application and verification of expert systems technologies to implement autonomous AR&D operations will require careful planning and performance evaluation.

Pathfinder technologies must build upon the rich heritage of piloted rendezvous and docking experience while providing on-board intelligence and instrumentation to assess anomalies and select alternate means to achieve mission objectives. Requirements for redundancy needed to achieve long-term planetary mission objectives which include long periods of dormancy of electronic and mechanical systems must be developed and, to the extent possible, demonstrated in an in-space environment that includes realistic lighting and thermal effects.

As NASA transitions to a mixed fleet capability, there will be opportunities to define in-space research and technology flight demonstrations using the NSTS, OMV, Space Station and expendable vehicles to build sufficient confidence to commit the very costly vehicles and systems that will be required for planetary exploration to a mission.

The management structure adopted for Pathfinder projects will be a key factor in capitalizing on high leverage opportunities for synergism between diverse NASA programs.

SECTION 6

Technology Transfer Planning

TBS

APPENDIX

PROGRAM ROLES, RESPONSIBILITIES, AND ACCOUNTABILITY

A Lead Center management organization structure has been proposed to manage the Pathfinder Automated Rendezvous and Docking (AR&D) Project. This type of management structure is well suited for defining and controlling these types of research and technology projects. Code RC has been designated the overall Program Manager for the Pathfinder AR&D effort, with an intercenter working group responsible for defining and planning the initial effort and serving as a steering committee. JSC has been designated as the Lead Center for managing the effort and providing the technical coordination with NASA HQ and the other participating centers.

Figure B.1 shows the management structure that has been selected.

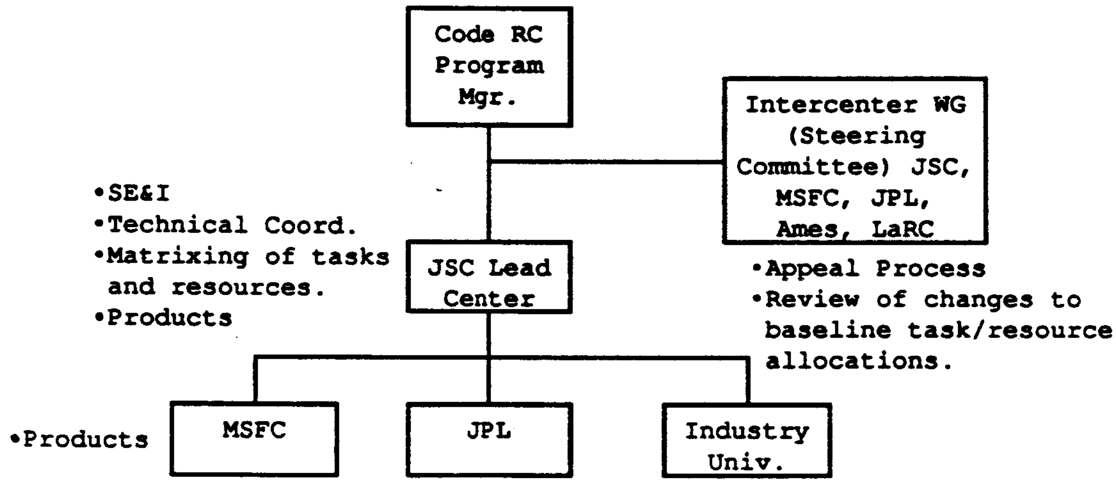


Figure B.1 - Management Structure for Pathfinder AR&D Project.

B-1 PROGRAM ROLES

NASA HQ (Code RC)

Code RC is the liaison between the Lead Center and the fiscal agents within NASA Headquarters to coordinate the budget requirements of the AR&D Project. They provide overall management guidance and ensure that the objectives of the AR&D project are compatible with the overall needs of Code RC and NASA. They also function as liaison between the Lead Center and other codes at NASA HQ.

Intercenter Working Group Steering Committee

The Intercenter Working Group (Steering Committee) functions as the project conscience in resolving disagreements between the different centers concerning the task and resource allocations. It consists of representatives from each of the participating and interested centers and acts as an advisor to the Program Manager at Code RC.

Johnson Space Center (JSC)

JSC functions as the Lead Center in providing day-to-day management of the conduct of the AR&D project. They also recommend resource and task allocations to Code RC to most effectively utilize NASA resources and capabilities. They will define the different system and artificial intelligence requirements, develop the required sensors, docking mechanisms, and proximity operations algorithms.

Marshall Space Flight Center (MSFC)

MSFC, as a participating center, will lead development of docking algorithms and will participate in ground demonstrations of docking mechanisms. They will manage the appropriate technology development efforts within their areas of responsibility.

Jet Propulsion Laboratory (JPL)

JPL, as a participating center, will formulate the Battin-Vaughan-Lambert (B-V-L) GN&C algorithm as part of the overall GN&C integration effort. They will manage the appropriate technology development efforts within their areas of responsibility.

Ames Research Center (ARC) and Langley Research Center (LaRC)

Ames Research Center (ARC) and Langley Research Center (LaRC) will participate as part of the Intercenter Working Group Steering Committee.

Industry

Industry contractors will participate as appropriate, according to those efforts they propose that are approved and funded by the appropriate NASA participating or interested centers. They will implement AR&D engineering components.

Universities

Universities may participate as appropriate, according to those programs they propose that are approved and funded by the appropriate NASA participating or interested centers. They may participate in development of artificial intelligence techniques implementation, and at technology workshops.

B-2 PROGRAM RESPONSIBILITIES

NASA/HQ (Code RC)

Code RC is responsible for the overall management of the AR&D Program. They are responsible for guiding budget requests through the necessary coordination process, and for transferring the resultant resource allocation to each center for subsequent allocation to the different tasks. The AR&D Program Manager will chair Steering Committee meetings and act upon their advisory recommendations as appropriate.

Johnson Space Center (JSC)

JSC, as the Lead Center, is responsible for the project management of the technology efforts of JSC and the other participating centers. They will provide the technical coordination between the participating centers' technology efforts and recommend resource and task allocations to Code RC. JSC is responsible for making all reports to NASA HQ on the progress of the technology efforts, and will track schedules and progress against agreed upon milestones. They will manage the scheduling of deliverables and tasks so as to ensure quality products in a timely manner. JSC shall have a representative on the Intercenter Working Group Steering Committee.

Marshall Space Flight Center (MSFC)

MSFC is responsible for managing the research tasks assigned to them within the budget and time constraints spelled out in the AR&D Project Plan. They will provide the deliverables called for in the AR&D Project Plan. MSFC shall have a representative on the Intercenter Working Group Steering Committee.

Jet Propulsion Laboratory (JPL)

JPL is responsible for managing the research tasks assigned to them within the budget and time constraints spelled out in the AR&D Project Plan. They will provide the deliverables called for in the AR&D Project Plan. JPL shall have a representative on the Intercenter Working Group Steering Committee.

Ames Research Center (ARC)

As an interested center, ARC may propose related technology efforts for funding within the AR&D Program in later years. For efforts that are funded, ARC will become a participating center and will be responsible for managing the research tasks they are assigned within the budget and time constraints of the Project Plan. ARC shall have a representative on the Intercenter Working Group Steering Committee.

Langley Research Center (LaRC)

As an interested center, LaRC may propose related technology efforts for funding within the AR&D Program in later years. For efforts that are funded, LaRC will become a participating center and will be responsible for managing the research tasks they are assigned within the budget and time constraints of the Project Plan. LaRC shall have a representative on the Intercenter Working Group Steering Committee.

Industry

Industry proposals that are funded will be managed by the appropriate contracting center. These efforts should support the technology tasks that are the responsibility of the participating centers. Where these efforts are contractor IR&D efforts, they should be coordinated with the center that has responsibility for the technology development in that area. Industry is to be encouraged to participate in this program to the maximum extent possible.

Universities

University participation in this project is to be encouraged to the maximum extent possible so as to bring research ideas to technology level 5 as early as possible. Universities should propose research efforts that support the objectives of this project to make maximum use of ideas.University research efforts should be directed toward the NASA center responsible for the applicable technology area.

B-3 PROGRAM ACCOUNTABILITY

The AR&D Program Manager shall provide the budget allocations as agreed to in the approved Project Plan for distribution to the appropriate tasks. He shall also provide management guidance as to project objectives and coordinate between the project and the various NASA HQ organizations needed to support the technology efforts.

JSC, as the Lead Center, is responsible to NASA HQ (Code RC) for the technical content of the AR&D project, and for meeting the schedules and reporting requirements of the AR&D Program Manager. They shall ensure that all technical efforts under the auspices of the project are satisfied within the budget and time constraints of the approved Project Plan.

MSFC and JPL, as the participating centers, are responsible to JSC for the technical content of the efforts under the management responsibility. They will manage their resources within the budget allocations and time constraints spelled out in the approved AR&D

Project Plan. Deliverables and required reports will be submitted to JSC for coordination with Code RC.

In cases of disagreement between the Lead Center and one or more participating center, the issue may be reported to the Intercenter Working Group Steering Committee. The Intercenter Working Group Steering Committee will listen to the issues involved and make a recommendation to the AR&D Program Manager.